An AC Josephson Source for Johnson Noise Thermometry

Samuel P. Benz, *Senior Member, IEEE*, John M. Martinis, Paul D. Dresselhaus, and Sae Woo Nam

Abstract—We have adapted the Josephson arbitrary waveform synthesizer to create a quantized voltage noise source suitable for calibrating the cross-correlation electronics of a Johnson noise thermometer system. The requirements of long term stability and low voltage amplitude allow dramatic simplification of the bias electronics compared to previous bias techniques. We describe the waveform synthesis, the bias technique, and the superconducting integrated circuit used to generate the pseudo-noise waveforms.

Index Terms—AC source, correlation, digital-analog conversion, frequency synthesizers, Josephson arrays, noise, quantization, superconducting microwave devices.

I. INTRODUCTION

THE goal of the Johnson noise thermometry program at NIST is to build an electronic temperature standard based on the quantized voltage pulses of superconducting Josephson junctions [1]. In a Johnson noise thermometer (JNT) system [2], the temperature T is inferred from a cross-correlation measurement of the Johnson noise voltage V_T across a calibrated resistance R. The mean-squared voltage noise is given by the Nyquist formula $\overline{V_T^2} = 4kTR\Delta f$, where Δf is the bandwidth for the measurement and k is Boltzmann's constant. Cross-correlation techniques are typically used to measure these extremely small voltages. A stable, programmable, and intrinsically accurate noise source would enable direct calibration of the cross-correlation electronics, matching of the calibration voltage noise to that of the sense resistor, and matching of the source impedance to both the sense resistance and the output transmission-line impedance. These features reduce the measurement uncertainty, increase the measurement bandwidth, and decrease the measurement time. In this paper, we describe a quantized voltage noise source (QVNS) having all these features. The correlation electronics and recent data taken using the full JNT measurement system are presented in an accompanying paper [3].

Using a QVNS we hope to achieve uncertainties of better than a few parts in 10^5 for temperatures in the range of a few hundred kelvins [1]. At these temperatures, the noise signals are small, on the order of 1 nV/Hz$^{1/2}$. However, in order to achieve small uncertainties for such low-voltage signals, the noise power spectral density must be integrated for a long time and/or over a wide bandwidth. Thus, the QVNS must be stable for long integration times but does not need to generate large voltages. These requirements allow the QVNS to be much simpler than

the Josephson arbitrary waveform synthesizer, where the primary focus has been to obtain the highest voltages [4]–[7].

Both the Josephson arbitrary waveform synthesizer and the QVNS produce voltage signals with calculable magnitudes based on the perfectly quantized voltage pulses of Josephson junctions, because the time-integrated area of every Josephson pulse is precisely equal to an integer number of flux quanta, $h/2e$, the ratio of Planck's constant to twice the electron charge. Knowledge of the number of pulses and their position in time is sufficient to precisely determine the time-dependent voltage of any synthesized waveform. Thus, digital synthesis using perfectly quantized pulses enables the generation of waveforms with amplitudes that are dependent only on fundamental constants and a time standard [4].

The biggest difference between the QVNS in the JNT application and the Josephson synthesizer for other applications is that the synthesized voltage signals have extremely small amplitudes. This is an advantage because the low voltages allow us to use the original concept for the pulse-driven Josephson digital-to-analog converter [4], which uses input pulses of only a single polarity. The simplified input bias scheme for the QVNS is shown in the block diagram of Fig. 1, where the Josephson array is biased with unipolar pulses from the code generator. This is much simpler than more recent bias schemes of the Josephson synthesizer, where large output voltages are achieved with bipolar pulses by adding a sine wave to the input drive [5], [6]. A desired analog pseudo-noise voltage waveform $V(t)$ is converted to a digital code by the modulator algorithm. Using this code, a two-level, 10-Gbit/s code generator drives two Josephson arrays using unipolar pulses from each of the data (D) and data-complement ($\bar{D}$) channels. Two separate differential voltage taps (V_A and V_B across the series-coupled arrays) and a common line are used for calibrating the cross-correlation electronics of the JNT system.

An important advantage of the QVNS unipolar approach is that it removes the difficulty of maintaining phase lock between the code generator and this sinusoidal drive. For the long integration times, perhaps hours or days, needed for the JNT, checking and maintaining phase lock would require complex automation and significantly increase the total measurement time. Further details of this unipolar QVNS bias technique are described in the "bias technique" section of this paper.

II. WAVEFORM SYNTHESIS

In order to calibrate the correlation electronics over its 1-MHz bandwidth [3], we synthesize a pseudo-noise waveform $V(t)$ which has a constant voltage spectrum over this bandwidth.
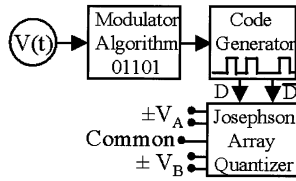
Fig. 1.   Block diagram of the quantized voltage noise source for Johnson noise thermometry.

Fig. 2.   Simulated time-dependent voltage of the first 40 μs of a synthesized pseudo-white-noise voltage waveform with 1258 harmonic tones, 6 291 456 bits, and 10-GHz clock frequency. The rms amplitude of each tone summed in this waveform is 51.55 nV and the relative phases are random. The voltage scale assumes an 8200-junction array and a $0.125V_{\max}$ dc offset voltage.

This can be done by generating a waveform where the lowest frequency and all of its harmonic tones have the same calculable voltage amplitude. The synthesizer uses a digital code that is M bits long and is repeatedly cycled through the circulating memory of the code generator. The synthesized waveform then has a minimum frequency called the pattern repetition-frequency, $f_1 = f_s/M$, where f_s is the clock frequency of the code generator. f_s is also the sampling frequency in the analog-to-digital conversion process of the modulator algorithm [8], [9]. The modulator algorithm that generates the digital code is a first-order two-level delta-sigma modulator. The modulator feedback uses a low-pass filter with zeros at dc.

The synthesized pseudo-noise waveform is constructed by summing harmonics of this pattern repetition frequency, where the relative phase of each harmonic tone is randomly chosen to more closely resemble a real noise waveform. The rms voltage amplitude of each tone $V_{\rm rms}$ is chosen to match the mean-square noise-voltage over the entire f_1 bandwidth for a resistor at some temperature such that $V_{\rm rms}^2 = 4kTRf_1$. Note that the voltage of the synthesized tones will appear larger than the voltage noise of the resistor because the mean-square voltage over each f_1 band is reduced to a single tone in the pseudo-noise waveform. Longer codes will allow smaller pattern repetition frequencies and closer tone spacing to produce more realistic pseudo-noise waveforms.

For a unipolar pulse drive, the minimum output voltage of a series array of junctions is zero and the maximum voltage is $V_{\max} = nNf_s/(2K_{J-90})$, where n is the number of quantized output pulses per input pulse (typically $n = 1$), N is the number of series junctions in the array, and $K_{J-90} = 0.483\,597\,9$ GHz/μV [4]. For the measurements and simulations presented in this paper the total number of junctions is $N = 8200$ and the clock frequency is $f_s = 10$ GHz, so that $V_{\max} = 84.78$ mV.

Fig. 2 shows the first 40 μs of the time-dependent analog voltage waveform of a typical pseudo-noise waveform ($V(t)$ in Fig. 1) before it is digitized by the modulator algorithm. This is also the periodic time-dependent waveform generated by the Josephson arrays, which can be measured directly on an oscilloscope after sufficient amplification. We chose 6 291 456 bits for the length of the resulting bitstream so that the pattern repetition frequency is 1.589 kHz. We also chose 1258 harmonic tones for this waveform in order to cover twice the 1-MHz measurement bandwidth [3]. The amplitude of each tone is chosen to be $8.6 \times 10^{-7} V_{\max}$, which corresponds to 51.55-nV rms for each tone when synthesized by the Josephson array. This amplitude is within 0.01% of the voltage noise of the 100-Ω resistor in
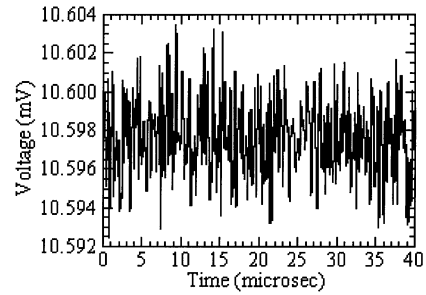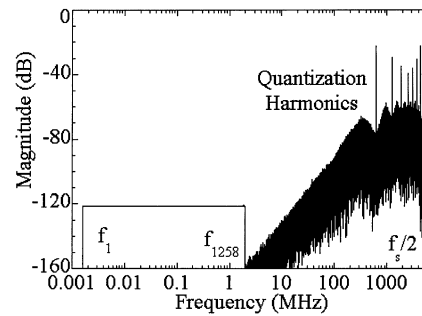

Fig. 3.   FFT of the simulated digital code from the delta-sigma modulator showing the voltage of harmonic tones up to the Nyquist frequency ($f_s/2$) of a 6 291 456 bit code clocked at $f_s = 10$ GHz. The magnitude in decibels is relative to $V_{\max}$. The first 1258 tones of the desired synthesized output waveform have the same amplitude. The harmonic amplitudes are not displayed as a typical stick histogram, but for clarity, they are connected by lines.

our Ga-triple-point cell when the 1.293 nV/Hz$^{1/2}$ voltage noise of the resistor at $T = 302.916$ K is integrated over the pattern repetition frequency ($\Delta f = f_1$).

The fast Fourier transform (FFT) of the corresponding digital code after the analog waveform is digitized by the modulator is shown in Fig. 3. The lowest tones in the FFT clearly have the same amplitude over the 2-MHz bandwidth. It also shows the typical behavior of the out-of-band harmonics where they increase up to the Nyquist frequency ($f_s/2$). These tones are caused by the discrete quantization in the analog-to-digital conversion as the delta-sigma modulator sequentially generates each bit of the digital code. The modulator pushes the unwanted quantization signals away from the low-frequency output band and up to higher frequencies, where they can be removed with low-pass filters. Using its perfectly quantized pulses, the Josephson array recreates this entire waveform, including the "quantization harmonics." The out-of-band harmonic signals (typically above 10 MHz) are usually removed by a low-pass filter. However, in order to maintain the flattest in-band frequency response for the JNT application we have not included an explicit low-pass filter on the Josephson array output leads. Many of the tones above 100 MHz propagate through the pass band of our cryoprobe and are then filtered in the cross-correlation electronics. Without this filtering unexpected signals are generated in the FETs of the initial amplifier stages [3].

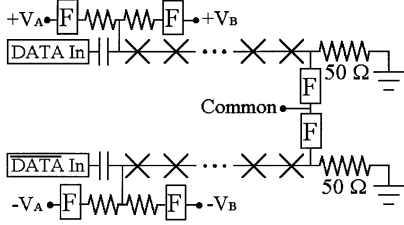BENZ *et al.*: AC JOSEPHSON SOURCE FOR JOHNSON NOISE THERMOMETRY.

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Fig. 4. Diagram of the superconducting integrated circuit for the quantized voltage noise source. Josephson junctions are indicated by Xs and low-pass filters by Fs. The two output voltages V_A and V_B across both arrays are applied to the differential inputs of the two cross-correlation channels.
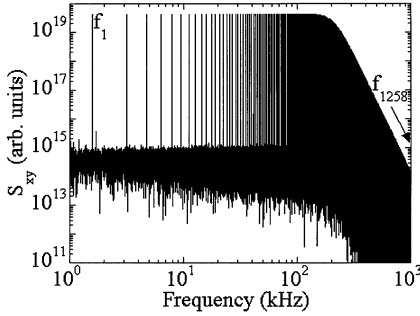

Fig. 5. Log–log plot of the measured cross-correlated power (V^2) spectrum S_{xy} of the 1258 tones synthesized by the QVNS and measured by the JNT electronics. Each bin has a width of 1 Hz and is an average of 200 samples. The power spectrum is in arbitrary units based on the digitizer bins.

III. QUANTIZER CIRCUIT DESIGN

The circuit design for the Josephson quantizer is shown in Fig. 4. Since a common reference point is needed for the correlation electronics, the quantizer is divided into two symmetric circuits with separate arrays of Josephson junctions. Each array is embedded in a 50-Ω coplanar waveguide transmission line that is terminated by a 50-Ω resistor. The data and data-complement signals drive each respective array through room-temperature dc blocking capacitors on the center conductors. The purpose of these blocking capacitors will be described in the next section. Either one or both outer conductors of the transmission line maintain a continuous ground between the code generator and the array circuit. The arrays are series-connected through superconducting low-pass filters [7]. The center point between these two filters at the terminated end of the two arrays is used as the common reference for the cross-correlation electronics. V_A and V_B are the output voltages across both arrays, and are applied to the differential inputs of the two cross-correlation channels. Each of these four taps has a 50-Ω resistor and a 3-GHz low-pass filter to keep the high-speed pulses in the coplanar transmission line. The 100 Ω total output resistance of each pair of taps matches the 100 Ω impedance of the twisted-pair output leads and is equal to the 100 Ω resistance of the sense resistor. For the results shown in this publication, these resistors are off chip on the BeCu spring fingerboard, and there is an additional on-chip 25-Ω resistor (not shown) on the common lead. The junctions are Nb-PdAu-Nb superconductor-normal metal-superconductor junctions of 2-μm diameter [10].

IV. BIAS TECHNIQUE

As mentioned in the introduction, the low voltages required for JNT allow us to simplify the QVNS input bias and to use only the high-speed pulses from the code generator to bias the Josephson arrays. This unipolar input drive causes the QVNS to produce precisely one output pulse for every input pulse, and thus a corresponding unipolar output waveform. Although the low JNT voltages allow us to simplify the high-speed bias, they pose a significant challenge for ensuring signal purity in the output signal that is measured across the Josephson quantizer. Therefore it is very important to minimize or remove all sources that could potentially generate unwanted but correlated signals in the output voltage leads within the 1-MHz measurement bandwidth of the cross-correlation electronics.

First, we address potential in-band signals from the digital code generator. The code generator signal has frequency components at exactly the same frequencies as the desired output voltage of the Josephson quantizer, namely those shown in Fig. 3. These signals can produce unwanted voltages on the output as a result of input-output coupling or due to current-induced voltages from the distributed transmission-line inductance between the junctions. These inductively coupled signals become even more significant at the highest in-band frequencies.

For the QVNS, we can reduce these unwanted signals by using dc blocks to ac couple the input drive signal to the quantizer. The blocks act as high-pass filters for the gigahertz-frequency pulses and as attenuators for the low-frequencies of the 1-MHz measurement band. This ac-coupled approach is also used for the Josephson synthesizer in order to remove common-mode signals on the transmission-line termination resistor [6], [7]. However, in order to maintain operating margins in the ac-coupled bias technique, the low frequency signals must be reapplied across the array through the low-speed leads. Fortunately, this is not necessary for the JNT application because the low-speed in-band signals have such small amplitudes (because the desired voltages are so low) that they provide negligible bias currents to the arrays.

The primary disadvantage of the unipolar bias is that a dc offset is always present in both the input and output waveforms. The modulator algorithm that we use generates a two-level bipolar nonreturn-to-zero (NRZ) code, switching between $+1$ and -1 levels [8], [9]. A dc offset naturally occurs when we convert this to unipolar $+1$ and 0 levels. This offset is necessary for current biasing the Josephson array on its operating margins. Furthermore, the Josephson array also generates this unwanted dc voltage, which can alter the performance on the FET input stage of the measurement electronics [3].

Fortunately, the dc offset can be minimized by applying a dc offset in the input waveform to the modulator algorithm. This causes the digital code to have many more zeros than ones so that the quantizer does not need to produce unnecessary pulses to generate the dc voltage. An additional advantage is that fewer pulses with large time delays between them results in increased operating margins for the Josephson array. We typically choose -0.75 as the bipolar offset, which corresponds to a unipolar dc offset of $A_{\text{offset}} = +0.125$. The corresponding dc offset across

the array is $A_{\text{offset}} \times V_{\text{max}}$, which is 10.6 mV for the data presented in this publication.

The dc blocks on the broadband code generator input will completely remove this dc bias as well as the in-band harmonic signals described earlier. When the dc offset is minimized in the input waveform, as described above, we have found that the Josephson quantizer can be biased within its operating margins by tuning the pulse amplitude of the digital code generator output signal. The operating margins for the QVNS are entirely optimized by adjusting this single parameter, the amplitude of the ac-coupled high-speed digital code signal. As shown in Fig. 1, in the simplified QVNS bias technique the two Josephson arrays in the quantizer are driven only by two high-speed bias signals, data (D) and data-complement ($\bar{D}$).

Since the pulse amplitude is the only remaining parameter adjusting the operating margins, there is no need for any additional low-speed leads, as are required for the high-voltage Josephson synthesizer applications. Removal of these leads reduces the QVNS circuit complexity as well as minimizing unwanted noise and input-output coupling signals on the total output voltage.

The measured cross-correlated power spectrum of the synthesized pseudo-noise voltage waveform is shown in Fig. 5. Although the mean-square voltage is shown in arbitrary units, through separate measurements we have determined that the gain of the amplifier chain is approximately 10^6. As a reference, the rms voltage of each tone is 51.55 nV, which should correspond to a rms value of 2.7e-15 V^2 at the input to the JNT electronics. The roll-off at 200 kHz is defined by digital filters in the measurement electronics [3].

V. CONCLUSION

We have described the bias technique and operation of the quantized voltage noise source. The requirement for small output voltage simplifies the input bias, while at the same time requiring us to make further simplifications of the bias scheme to avoid unwanted signals in the dc-to-1 MHz measurement band. The optimized QVNS bias technique allows us to bias the Josephson-array quantizer within its operating-current margins by adjusting a single input parameter, the pulse amplitude of the digital code generator. By means of the cross-correlation electronics, we have successfully measured pseudo-noise waveforms synthesized with this bias technique and found that the operating margins of the QVNS can be maintained for many hours so that long integration times reduce the uncorrelated noise and decrease the measurement uncertainty.

ACKNOWLEDGMENT

The authors would like to thank W. Tew, F. Walls, C.J. Burroughs, and R. White for their helpful comments.

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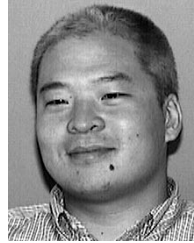
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